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A HEIGHT-COMPUTER FOR USE IN AEROLOGICAL WORK

By E. G. BILHAM, B.Sc., D.I.C.

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A HEIGHT-COMPUTER FOR USE IN AEROLOGICAL WORK

By E. G. Bilham, B.Sc., D.I.C.

1. **Fundamental Relationships.**—In computations related to the changes of pressure, temperature and density in the atmosphere we may assume that the atmosphere behaves as a perfect gas, fulfilling the fundamental relationship

$$p = k \rho T \qquad \text{(i)}$$

Where p is the pressure, ρ the density, T the absolute temperature, and k a constant. Also, assuming that at any point any vertical acceleration is negligible in comparison with the gravitational acceleration g we may write

$$dp = -g \rho \, dz \qquad \text{(ii)}$$

expressing the fact that the decrease of pressure due to an increment dz of height is equal to the weight per unit area of an element of thickness dz. Combining (i) and (ii) we obtain :—

$$\frac{dp}{p} = \frac{-g}{k} \cdot \frac{dz}{T}$$

whence by integration between the limits $p - p_o$, $z - z_o$

$$\log \frac{p_o}{p} = \frac{g}{kT_m}(z - z_o) \qquad \text{(iii)}$$

where p_o is the pressure at standard height z_o and p, that at height z, T_m being the reciprocal of $\dfrac{1}{z - z_o}\displaystyle\int_{z_o}^{z} \frac{dz}{T}$ and therefore equal to the harmonic mean value of the temperature at equal steps of height, between z_o and z. (Strictly, account should be taken also of the variation of g with height. This is a point to which we shall return later).

(iii) may be written

$$z - z_o = \frac{k}{g \log_{10} e} \cdot T_m \log_{10} \frac{p_o}{p}$$

or writing C for the constant factor $k/g \log_{10} e$ and h for the interval $z - z_o$

$$h = C. \, T_m. \log_{10} \frac{p_o}{p} \qquad \text{(iv)}$$

which is the fundamental equation for evaluating height from observations of pressure and temperature in the atmosphere.

Taking the standard values $p_o = 1013{\cdot}23$ mb., $T_o = 273°$ A, $\rho_o = 1293{\cdot}052$ gm./m^3 and $g = 980{\cdot}617$ cm./sec.^{2} we obtain the following working equations :—

$$\text{Heights in metres ; } h = 67{\cdot}40\ T_m \log \frac{p_o}{p} \qquad \text{(v)}$$

$$\text{Heights in feet ; } h = 221{\cdot}1\ T_m \log \frac{p_o}{p} \qquad \text{(vi)}$$

where p_o is now the pressure at mean sea level.

2. Practical Application to Reduction of Observations made on

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regular intervals of height during an ascent we could use equation (vii) to compute the corrections to be applied to the indicated heights in order to obtain true heights. This method is frequently adopted when accurate values of the height of an aircraft are required. In connexion with routine observations for meteorological purposes, however, it is better to deal with direct observations of pressure, the temperature being noted when the pressure passes through certain definite values. The main object of this paper is to explain how to determine heights from such corresponding readings of pressure and temperature by a simple mechanical method. The device to be described was introduced in 1922 to meet the need for a rapid and reasonably accurate method of dealing

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where p_o is now the pressure at mean sea level.

2. Practical Application to Reduction of Observations made on Aeroplanes.—By means of equation (vi) it is possible to compute heights in feet corresponding to a series of simultaneous observations of temperature and pressure in the upper air. If assumptions are made in regard to T_m, the harmonic mean temperature of the air column, this equation also provides a means for fitting a height scale to an aneroid barometer, which thus becomes an " altimeter". In " trade-scale " altimeters T_m is assumed to be constant and equal to 283°A. (50°F.). This scale is gradually being superseded by the scale adopted by the International Commission for Aerial Navigation (I.C.A.N.), in which the temperature is assumed to fall at a uniform lapse rate from 288°A. at sea level to 216·5°A. at 11 Km. and to have the constant value 216·5°A. at heights above 11 Km., an assumption which corresponds approximately with average conditions over the British Isles*. With either type of altimeter it is clear, however, that the indicated height would not ordinarily be the true height. If h and h' are the true and indicated heights, T_m and T'_m the true and assumed values of the mean temperature of the air column, it is clear from (iv) that

$$\frac{h}{h'} = \frac{T_m}{T'_m} \qquad \text{(vii)}$$

If T_m could be ascertained by taking temperature readings at regular intervals of height during an ascent we could use equation (vii) to compute the corrections to be applied to the indicated heights in order to obtain true heights. This method is frequently adopted when accurate values of the height of an aircraft are required. In connexion with routine observations for meteorological purposes, however, it is better to deal with direct observations of pressure, the temperature being noted when the pressure passes through certain definite values. The main object of this paper is to explain how to determine heights from such corresponding readings of pressure and temperature by a simple mechanical method. The device to be described was introduced in 1922 to meet the need for a rapid and reasonably accurate method of dealing

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with the upper air data supplied to the Forecast Division of the Meteorological Office, by the observers of the Meteorological Flight, Duxford. It has proved satisfactory for that purpose and copies of the instrument (modified to meet local needs) have since been supplied to certain outstations.

3. **Principle of the Method.**—Suppose (Fig. 1) that we set out a logarithmic pressure scale running from 400 mb. to 1050 mb. and select some arbitrary value of the mean air temperature, say 273°A. From equation (vi) it is clear that we could graduate a height scale, which would be uniformly divided and which would, when applied to the logarithmic pressure scale, give corresponding values of height in all positions, so long as the mean air temperature was equal to 273°A. Such a height scale is shown in contact with the pressure scale in Fig. 1. In this illustration the height scale is shown set with its zero over 1000 mb. on the pressure scale and in this position we obtain the height corresponding to any pressure in an isothermal atmosphere at a temperature of 273°A when the sea level pressure is 1000 mb. By sliding the pressure scale along to the left until 1050 mb. comes under the zero of the height scale we obtain corresponding readings for a sea level pressure of 1050 mb.

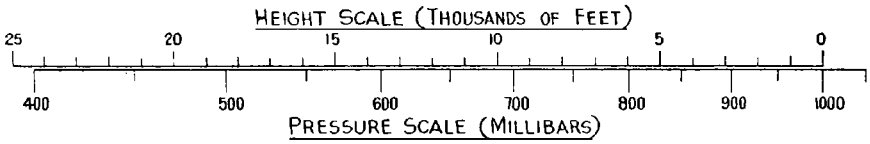

FIG. 1.

If we required to evaluate heights corresponding to a higher reading of air temperature, say 283°A. it would appear necessary to construct a fresh height scale in which the spacing between successive graduations was decreased in the ratio 273/283. We can, however, adopt an alternative method which avoids the necessity for constructing a new scale. The alternative is to use the method of oblique projection illustrated in Fig. 2. Here the original height scale is shown rotated through an angle α about its zero (which we suppose to remain in contact with the pressure scale at the point corresponding to the surface pressure). If by means of a set square we project any pressure reading (say 500 mb.) on to the height scale it is clear that the reading so obtained will be increased as compared with that shown in Fig. 1 in a definite ratio depending on the angle α through which the height scale is rotated. It is a matter of simple trigonometry to calculate the amount of rotation α necessary to give height readings corresponding to the assumed value of the mean temperature, 283°A. It is clearly given by the relation

$$\cos \alpha = \frac{273}{283}$$

This is equal to 0·96467, whence $\alpha = 15° 17'$ approx. Having set the height scale at this angle to the pressure scale, we could thus, by setting off a perpendicular to the pressure scale at any point obtain the height when the mean temperature is 283°A. As before we assume that the value of the sea level pressure is brought under the zero of the height scale by sliding the pressure scale to left or right, parallel with itself. In a similar way, by varying the angle between the two scales, we could obtain height readings corresponding with any value T_m of the mean temperature above 273°A., using the relationship

$$\cos \alpha = \frac{273}{T_m}$$

to determine the angle α.

The method could not be applied, in this example to values of T_m below 273°A., that temperature being the value we assumed when graduating the height scale for use in contact with the pressure scale, i.e. corresponding with $\alpha = 0$. The selection of the " basic "

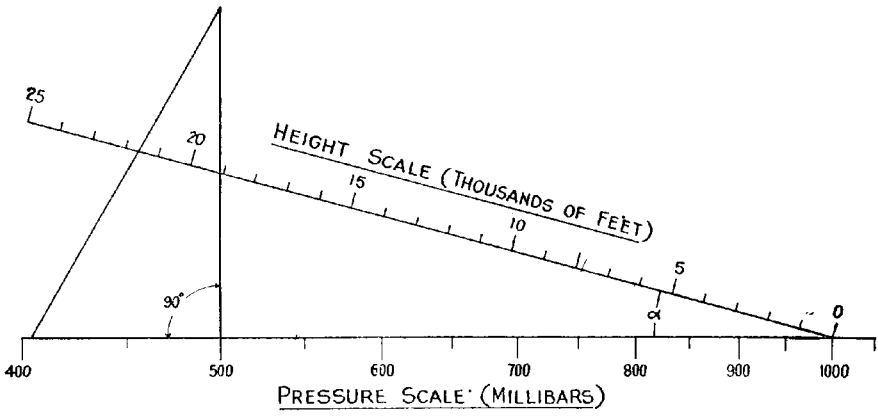

FIG. 2.

temperature is, however, purely arbitrary. We might equally well have chosen a temperature such as 260°A. as the basis for graduation. In constructing an instrument for regular routine use, it is merely necessary to select a value slightly below the lowest value of T_m likely to be met with in practice, to graduate the height scale accordingly and then to set off on an arc, the positions corresponding with various values of T_m up to the highest values encountered in practice.

4. **Details of an actual Instrument.**—From the discussion in the preceding paragraph it will be seen that a convenient instrument for the evaluation of heights can be constructed from the following parts :—

(*a*) A logarithmic pressure scale arranged so that it can be moved laterally parallel with itself through a distance equivalent to the range of pressure met with in practice at sea level.

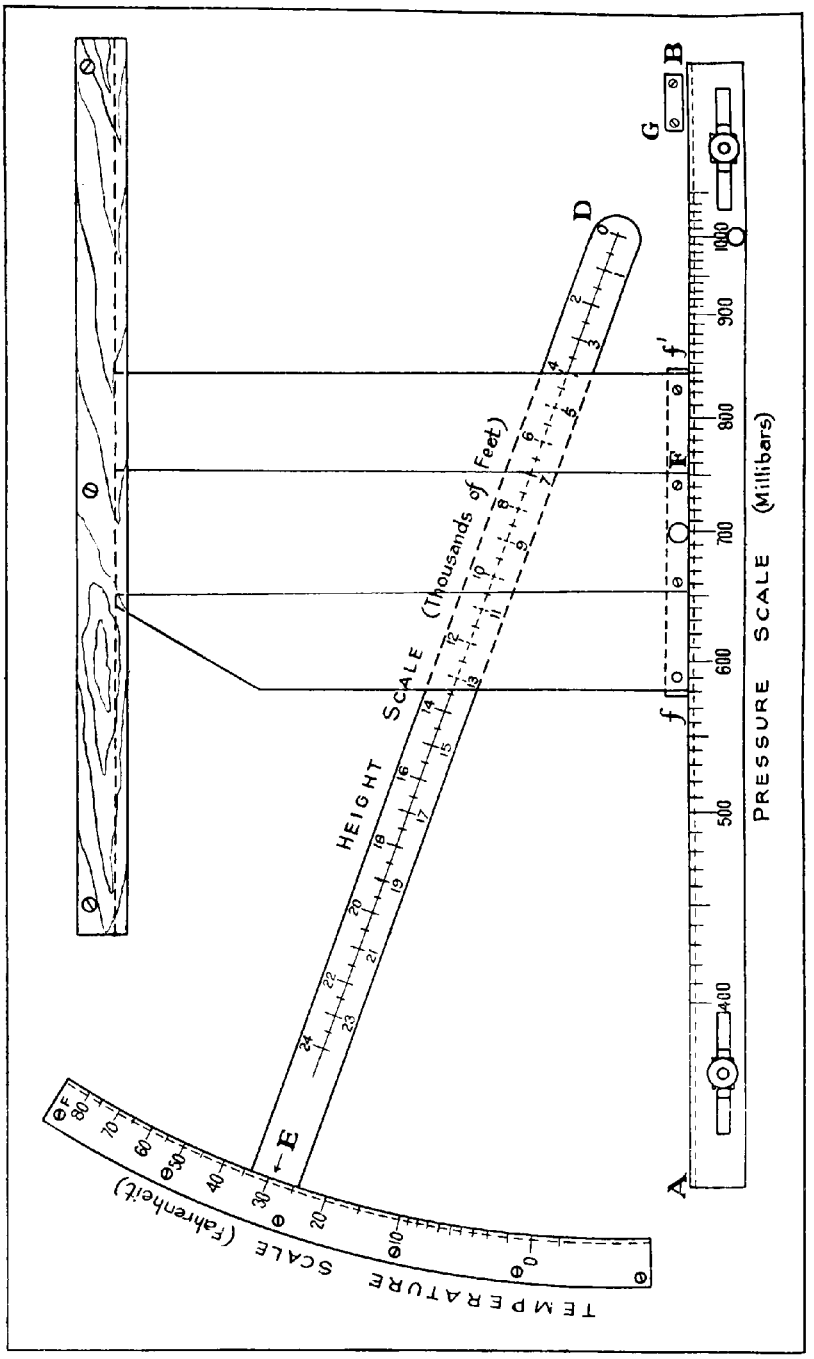

FIG. 3—DETAILS OF THE INSTRUMENT CONSTRUCTED IN 1922

(*b*) A uniformly divided height scale engraved on a radial arm rotating about a fixed point near the high pressure end of the pressure scale.

(*c*) A temperature scale in the form of an arc, the centre of the arc being the point about which the height scale rotates.

(*d*) A set square or cursor for projecting the pressure readings on to the height scale.

(*e*) A base board upon which the scales etc. are mounted.

The following details relate to an instrument constructed in 1922. The general appearance of the instrument will be gathered from Fig. 3 which is approximately to scale. The pressure scale (400 to 1050 mb.) is engraved on a strip of hard brass AB the scale being such that 1 cm. corresponds to a difference of 0·01 in $\log_{10} p$. The lateral movement is provided by slots at either end, through which pass screws carrying clamping nuts. Side-play is avoided by the use of suitable guides. The graduated edge is undercut to take a corresponding projection on the slider *ff'* which carries the cursor. The latter consists of a sheet of stout celluloid, the further edge of which travels under a wooden guide screwed to the base board near its upper edge. In this way a satisfactory sliding movement is obtained and the cursor lines remain strictly perpendicular to the edge of the pressure scale. To avoid the need for extending the cursor guides a considerable distance beyond the limits of the pressure scale, two cursor lines are provided, one near the left edge, the other near the right edge of the cursor.

The height scale is also engraved on a hard brass strip DE, the point of rotation D being coincident with the zero of the scale. A stout steel spindle passing through a bearing anchored to the back of the base board gives smooth rotation free from side-play. At its far end E, the brass strip is cut away to permit of its moving in a rebate on the inner edge of the arc upon which the temperature scale is engraved, a fiducial mark being provided for setting purposes. The height scale is sub-divided to 100 ft. and covers the range 0 to 24,000 ft., the scale value being 1,000 ft. = 0·7 in. which corresponds to a " basic " temperature of −1·6°F. The upper limit of the temperature scale is 80°F. and divisions are shown for each 1°F.

When the slider, carrying the celluloid cursor, is pushed towards the right it comes up against a stop G and the right hand cursor line F is then exactly over the zero of the height scale. To set the instrument for use it is then only necessary to unclamp the pressure scale, move it along until the sea-level pressure reading is shown against the cursor line F and reclamp it. As the height scale moves rather stiffly over the surface of the base board no clamp is necessary to fix it in position and none is provided.

5. **Manipulation.**—The data provided are readings of temperature, at ground level and at pressures of 950 mb., 900 mb., 850 mb., 800 mb. and so on.* The barometer is read at the beginning of an ascent and the temperature at the surface is also ascertained by reading a thermometer in a Stevenson screen. We thus have a series of readings corresponding to irregular intervals of height, but, apart from the first stage (ground to 950 mb.) to uniform intervals of pressure. The computer proceeds as follows :—Having adjusted the pressure scale as described in section 4 above, he obtains the mean temperature T_m' in the layer, ground to 950 mb. by working the arithmetic mean of the two temperature readings T_0 and T_1. He now sets the radial arm so that the fiducial mark at E (Fig. 3) reads T_m' on the temperature scale and moves the cursor until the foot of the cursor line F is against 950 on the pressure scale. The intersection of the cursor line on the height scale gives the height h_1 at which the pressure was 950 mb. and the temperature was T_1. He now moves the cursor to the point 900 on the pressure scale and sets E to the value T_m'' obtained by working the arithmetic mean of the temperatures T_0, T_1 and T_2, the latter being the reading at 900 mb. The height read under the cursor line is then entered as that for the 900 mb. reading, and so on. In each case the value of the quantity T_m in equation (vi) is assumed to be equal to the arithmetic mean of all the readings up to the point in question, and the entire thickness of the atmosphere up to that point is dealt with as a single layer.

6. **Sources of Error.**—In considering sources of error we must assume that the original observations are exact and that the constant in the basic equation (vi) is also correct. Any errors in these quantities would affect the result in the same way if the computations were made by logarithms. All we need concern ourselves about are, therefore, errors introduced by the instrument itself or by the method employed in its manipulation.

In the instrument described in section 4 the dimensions are such that settings of the pressure and temperature scales can be made by estimation to 1 mb. and 0·1°F. respectively and the height scale can be read by estimation to 10 ft. The magnitude of the errors arising purely from instrumental causes can be ascertained by comparing the heights worked on the instrument with those computed by logarithms using the same data. Comparisons made in this way show that instrumental errors are of the order of 10 or 20 ft., that is to say they are negligible for practical purposes.

In regard to manipulation, it is explained in section 5 that the value of T_m is obtained by taking the arithmetic mean of the readings

* A reading is actually taken also at 1,000 ft. as indicated by the pilot's altimeter. This reading is dealt with in the manner explained in section 9b and the value of pressure at the level of reading is then used in the way now to be described.

at the ground, and then at 950 mb., 900 mb. .... up to the point of observation. It has been assumed that this process gives the temperature of the equivalent isothermal atmosphere and it is evident that the accuracy of the computation of height is entirely dependent on the accuracy of this assumption. In practice, the true value of T_m is never known and a direct determination of the error arising from an inexact evaluation of T_m is, therefore, impossible. We can, however, form an estimate of the order of magnitude of the error by considering the ideal case of an atmosphere with a uniform lapse rate. We will take the case of the I.C.A.N. standard atmosphere in which the temperature T_z in degrees absolute is given by the equation

$$T_z = 288 - 0{\cdot}0065\, z$$

z being the height in metres. The sea level conditions are $T_0 = 15°\text{C.}$, height of barometer corrected to 0°C. = 760 mm. of mercury. The value of g is taken as 980·62 at all heights. From these values it follows that $p_0 = 1013{\cdot}17$ mb. Also, in the fundamental equation

$$\frac{dp}{p} = \frac{-g}{k} \cdot \frac{dz}{T}$$

we may put $$dz = -\frac{dT}{{\cdot}0065}$$

whence $$\frac{dp}{p} = \frac{g}{{\cdot}0065k} \cdot \frac{dT}{T}$$

or, by integration

$$\log \frac{p_z}{p_0} = \frac{g}{{\cdot}0065k} \cdot \log \frac{T_z}{T_0}$$

The value of $g/{\cdot}0065k$ is 5·256 and since p_0 and T_0 are known, this relation enables us to calculate the value of T corresponding to a given pressure. The value of the harmonic mean temperature can also be calculated directly. It is equal to the reciprocal of

$$\frac{1}{z - z_0} \int_{z_0}^{z} \frac{dz}{T_0 - T}$$

i.e. to the reciprocal of $$\frac{1}{T_0 - T_z} \int_{T_z}^{T_0} \frac{dT}{T}$$

the value of which is $$\frac{T_0 - T_z}{\log_e T_0 - \log_e T_z}$$

In Table I, the values of T corresponding to each pressure are given in column (2), and the harmonic mean temperatures for equal intervals of height from the ground to each pressure level are given in column (5). Column (3) gives the arithmetic means of the temperatures read at each pressure level ; for example, the value of 274·9

opposite 600 mb. is the arithmetic mean of all the temperatures in the first column from 288·0 up to 260·68. Column (4) gives the arithmetic mean of the temperatures at sea level and the pressure level; for example the value 274·3 opposite 600 mb. is the arithmetic mean of 288·0 and 260·68. Column (6) shows, to the nearest 10 ft., the actual height computed from equation (vi), using the harmonic

TABLE 1

		Mean Temperature of air column (T_m).				Error in height.	
p	T	Mean of readings at points of observation.	Arithmetic Mean $\frac{1}{2}(T + T_o)$	Harmonic Mean.	True height.	Using values of T_m in Col. 3.	Using values of T_m in Col. 4.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
mb.	°A	°A	°A	°A	ft. × 1000	ft.	ft.
400	$241\cdot3_2$	266·9	264·7	264·0	23·56	259	61
450	$246\cdot7_9$	269·1	267·4	266·8	20·83	177	47
500	$251\cdot7_9$	271·1	269·9	269·5	18·30	108	27
550	$256\cdot4_0$	273·0	272·2	271·9	15·93	64	18
600	$260\cdot6_8$	274·9	274·3	274·1	13·80	40	11
650	$264\cdot6_8$	276·6	276·3	276·1	11·77	21	7
700	$268\cdot4_3$	278·3	278·2	278·2	9·87	10	4
750	$271\cdot9_8$	280·0	280·0	279·9	8·10	3	2
800	$275\cdot3_4$	281·6	281·7	281·6	6·39	..	1
850	$278\cdot5_4$	283·2	283·3	283·3	4·76	..	..
900	$281\cdot5_8$	284·7	284·8	284·8	3·23	..	..
950	$284\cdot4_9$	286·2	286·2	286·3	1·77	..	..
1013·2	288·0	..	..	..	..	..	..

mean temperature given in column (5). Column (7) shows the error in height arising from the use of the inexact temperature means in column (3), and column (8) shows the errors arising from the inexact temperature means in column (4). The figures in both these columns were computed directly from the errors in mean temperature. It is of interest to note that the error is in every case positive, that is to say, the computed height is greater than the true height.

Column (7) is of chief interest because it sets out the errors arising from the method described in section 5 for computing the mean temperature of the air column. It will be seen that the error is only one part in a thousand at a height of about 10,000 ft., but increases very rapidly to about one per cent at 20,000 ft. Even at the greatest heights, however, the error is not large enough to be serious. The results given in the last column show that in the particular case we have considered the errors arising from taking the average of the temperatures at the top and bottom of the air column as the value of T_m are very small indeed. It must be remembered, however, that we have taken the case of a uniform

lapse rate. In practice, inversions of temperature are fairly common and when these are present a method which ignores the temperatures at intermediate levels may be attended by large errors. Suppose, for instance that the temperature at 400 mb. had been 250°A., representing an inversion of 3·3°A. The arithmetic mean would have been $\frac{1}{2}$ (288 + 250) = 269°A. The true harmonic mean would have been approximately 264·7°A. and the error in computed height would be about 400 ft. Consequently, it is better to adopt for general routine the method of averaging the temperature readings at all the points of observation, although it is known to give results which are too high because the readings are taken at closer intervals of height near the ground where the temperature is higher.

In actual practice also there is another factor which tends to make the errors smaller than are indicated by column (7) of Table I. The computation is carried out on the assumption that the air is dry. Since the density of water vapour is only about five-eighths of the density of air at the same temperature and pressure, the thickness of a layer of dry air required to produce a given pressure is appreciably less than that of a layer of moist air at the same temperature. Consequently, since our computations take no account of water vapour the computed heights are too low. In an average case the error arising from this cause would affect the result at the 500 mb. level by about two parts in a thousand, thus reducing the error of the final result by nearly fifty per cent.

7. Error arising from the variation of gravity.—For the graduation of the apparatus the value of g was taken as 980·617, the standard value at mean sea level in latitude 45°. The variation of g with height (z) and latitude (λ) is given by the equation

$$g_{z,\lambda}/g_{0,45} = (1 - 0{\cdot}00259 \cos 2\lambda)\,(1 - 5z/4E)$$

E being the radius of the earth expressed in the same units as z the height. Since meteorological aeroplane ascents do not often exceed a height of 4 miles and E is 4,000 miles, the error due to variation of g with height will never much exceed one part in a thousand and may be ignored. The factor $(1 - 0{\cdot}00259 \cos 2\lambda)$ has the value 0·9974 on the equator, 1·001 in latitude 57° and 1·0026 at the poles. The greatest variations due to the combined effects of height and latitude are thus found at the equator where the error amounts to about 4 parts in a thousand at a height of four miles, the indicated heights being too low.

8. Determination of Geopotential.—The fact that the instrument takes no account of the variation of gravity, means in practice that it yields results which are not true geometric heights but are approximations (arithmetically) to the values of geopotential at the points of observation. By substituting 1000 for 980·617 as the value for g in the reduction formula we can obtain the numerical value of the

constant C in equation (iv) for obtaining geopotential in "geodynamic metres". We thus derive for the value of H in geodynamic metres

$$H = 67{\cdot}27\ T_m \log \frac{p_0}{p}$$

In the instrument described in section 4 geopotential could be read off directly by substituting, for the height scale engraved in thousands of feet, a scale in which 1000 geodynamic metres was represented by a length of 2·301 in.

In the absence of such a scale geopotential in geodynamic metres is ascertained by multiplying the indicated heights in feet by the factor $67{\cdot}27/221{\cdot}1 = 0{\cdot}3043$.

9. Other uses of the Instrument.—The apparatus may be used for a number of purposes depending upon the solution of the logarithmic equation. Among these are the following :—

(a) *To determine the corrections to a trade-scale altimeter for any value of the mean temperature.*—Clamp the pressure scale in any position and set the radial arm to read 50°F. Adjust the cursor line over the height reading as given by the altimeter. Without moving the cursor rotate the radial arm to the given temperature reading. The true height will then appear under the cursor line.

(b) *To determine the pressures corresponding to the trade-scale altimeter graduations for any value of the surface pressure.*—Set the radial arm at 50°F and the surface pressure against the index. The required pressures are then obtained by projecting the height-scale readings on to the pressure scale.

(c) *To determine the mean temperature from the barometer readings at a mountain station and at sea level.*—Set the sea level reading (obtained from the isobars or from a neighbouring low-level station) under the index and set the cursor against the reading at the mountain station. Rotate the radial arm until the height of the station appears under the cursor line. The mean temperature can then be read off from the temperature scale.

10. An instrument with extended range.—In its orginal form, as described in the preceding sections, the instrument is designed for the determination of heights up to 24,000 ft. In recent years the need has been felt for a greater range of height. It will be realized from a study of section 6, that the limit to the range of height is really set by the magnitude of the error in the adopted value of T_m, the harmonic mean temperature between sea level and the maximum height to be computed in a single operation. The error increases rapidly with the height, and it is inadvisable, therefore, to extend the range merely by extending the pressure scale

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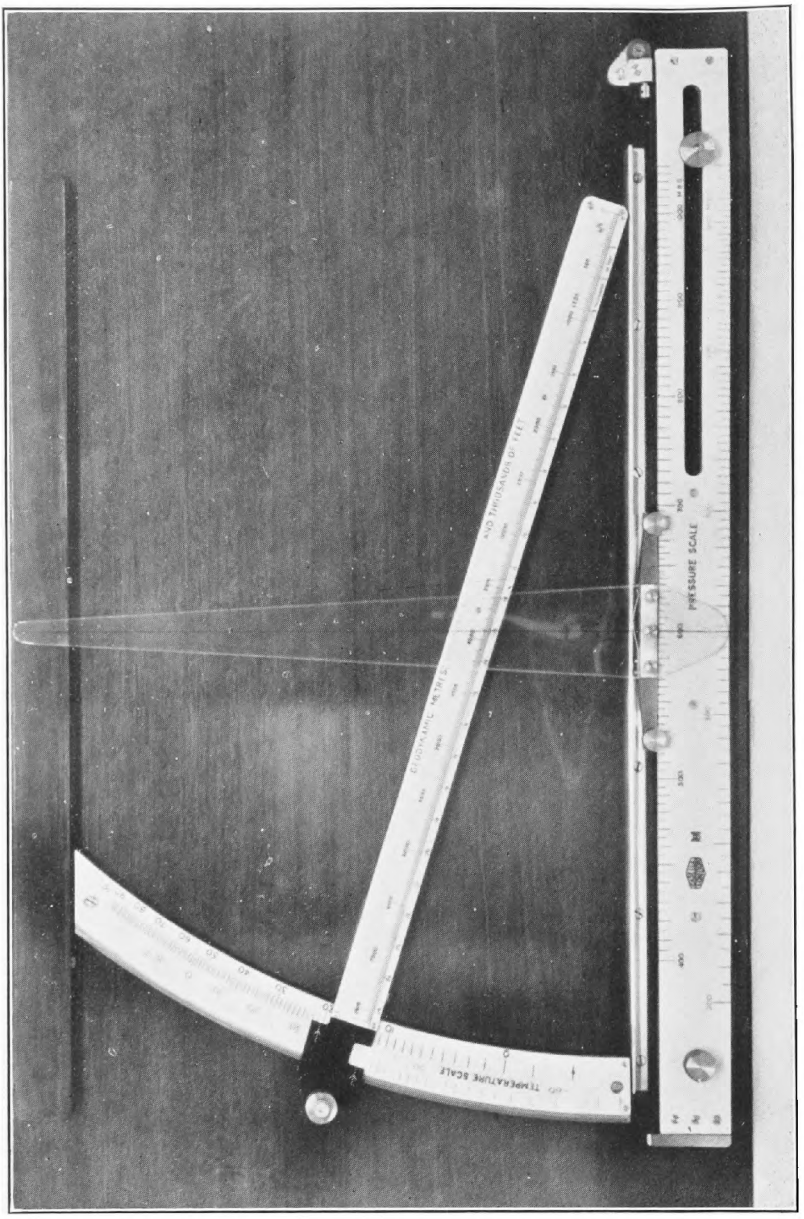

FIG. 4—MODIFIED HEIGHT-COMPUTER WITH PROVISION FOR DETERMINING HEIGHTS UP TO 50,000 FEET IN TWO STAGES

and the height scale. When it is desired, therefore, to deal with observations extending to lower pressures than those provided for in the original design it is necessary to carry out the computation in two stages.

The necessary modifications have been made in the most recent form of the instrument which is illustrated in Fig. 4.

The pressure scale for the range 400 to 1060 mb. is engraved in black on the upper edge of an ivoiine strip, and a second or low-range scale (200 to 650 mb.) in red on the lower edge.

The height scale is graduated in kilometres (0 to 7) and geodynamic metres (0 to 7,600), as well as in thousands of feet.

There are two temperature scales, the high-range scale (—1° to 90°F.) engraved in black, and the low-range (—61° to 10°F.) in red. The arm bears a fiducial mark for each scale.

When this instrument is being used, if the pressure or temperature reading passes beyond the lower limit of the high-range scale, the last stage reached on this scale is taken as a new starting point and the working is continued on the two low-range scales, T_m is then the mean of temperature readings at and above this point and the resulting heights are added to the height at this point.

In addition to the duplication of the scales the new instrument also incorporates certain mechanical improvements designed to facilitate its use and accelerate the working. Acknowledgments are due to Mr. A. E. Mayers and to Mr. J. S. Dines, Superintendent of the Instruments Division of the Meteorological Office, for the preparation of the new design.

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